Conceptual Problems (2): Land Surface Data Assimilation: where are we at?

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Soil Moisture Data Assimilation

Snow Data Assimilation

Terrestrial Water Storage Assimilation

Modeling, Re-Analysis

Gaps in Our Understanding

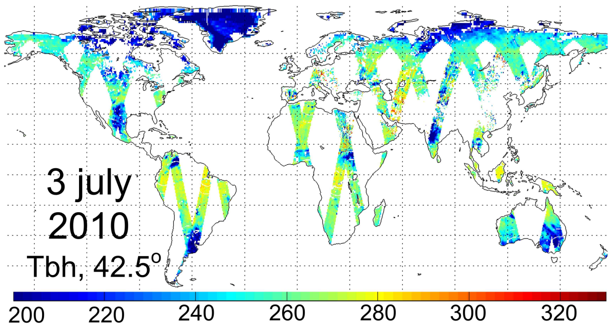
Conclusions

Soil Moisture Data Assimilation

Assimilation of Surface Soil Moisture

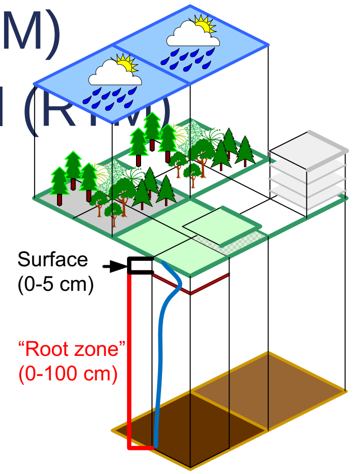
AMSR-E/SMOS/SMAP/. . . surface obs

- only 5 cm depth, coarse scale
- limited coverage in space and time
- measurement error



Ancillary information

- data assimilation parameters
- land surface model (LSM)
- radiative transfer model (RTM)
- surface meteorology



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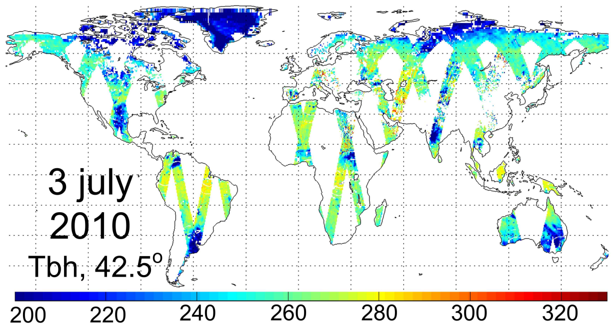

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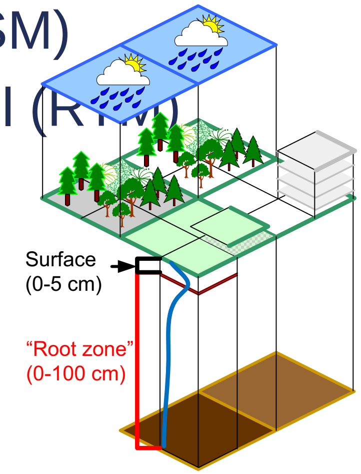

Data Assimilation

- Surface soil moisture ($\sim$ top 5 cm)
- Root zone soil moisture ($\sim$ top 1 m)
- Other geophysical fields

$\Rightarrow$ continuous, fine-scale, with error estimates

GMAO works on SMAP L4_SM

Assimilation of Surface Soil Moisture

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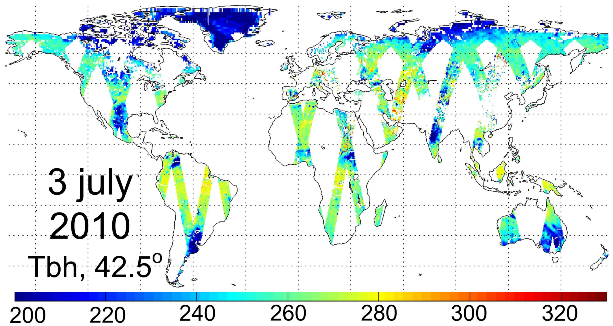

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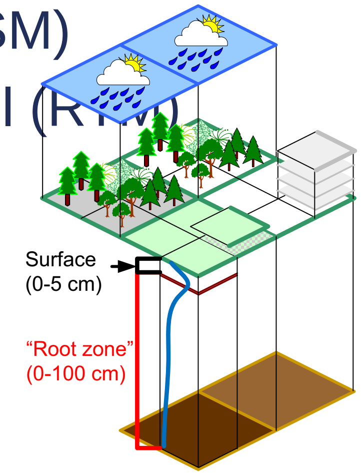


Data Assimilation

- Surface soil moisture (∼ top 5 cm)
- Root zone soil moisture (∼ top 1 m)
- Other geophysical fields

⇒ continuous, fine-scale, with error estimates

GMAO works on SMAP L4_SM

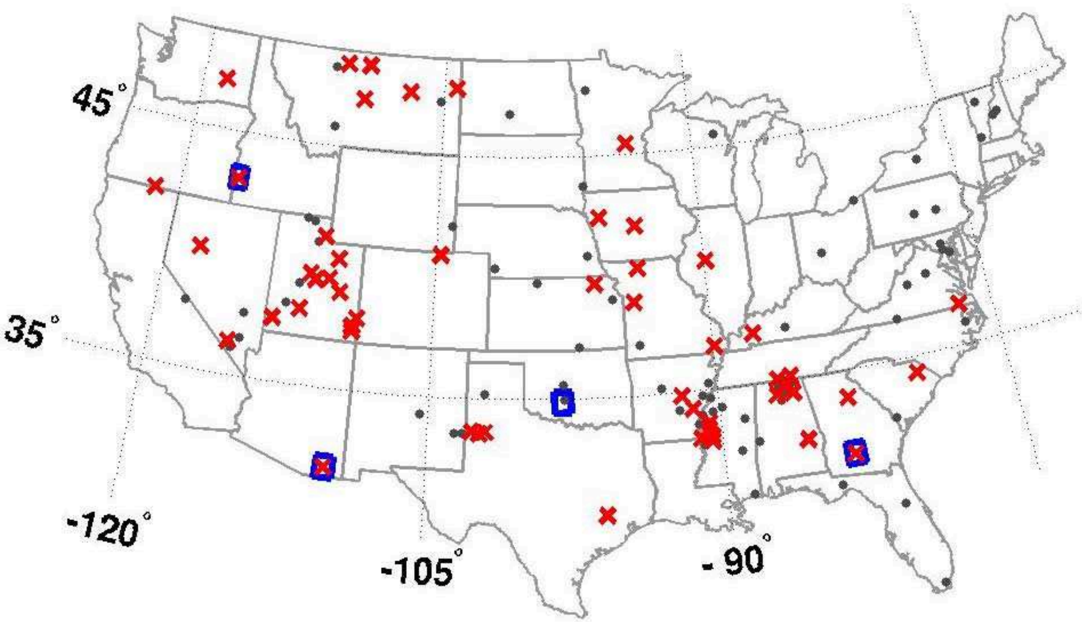
Validation: in situ ground measurements

Remote Sensing of Soil Moisture

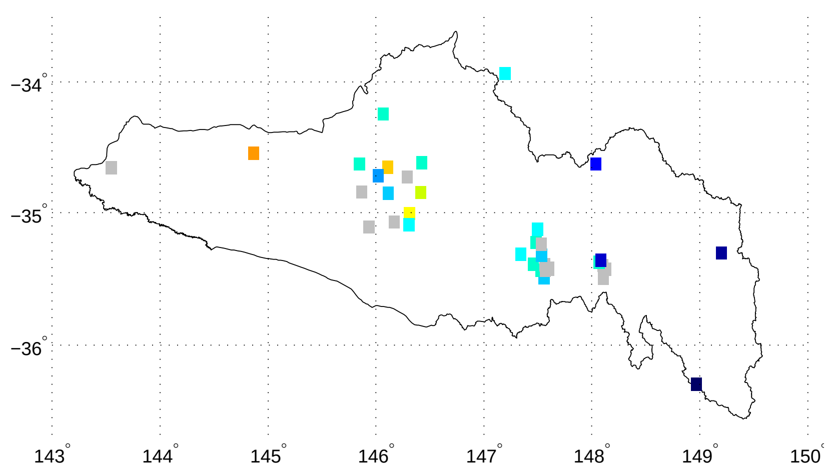
- active/passive microwave
  - actual measurements: brightness temperature or backscatter; retrieval: soil moisture
  - $\Rightarrow$ assimilate radiances or retrievals
- lower frequency $\longrightarrow$ deeper penetration depth
  - better correlation between surface observations and root-zone soil moisture
  - correspondingly adjust model structure
- resolution: 3-40 km
  - downscaling, scale mismatch with model

USA:

- SCAN (×): point measurements
- USDA CalVal (□): watershed average



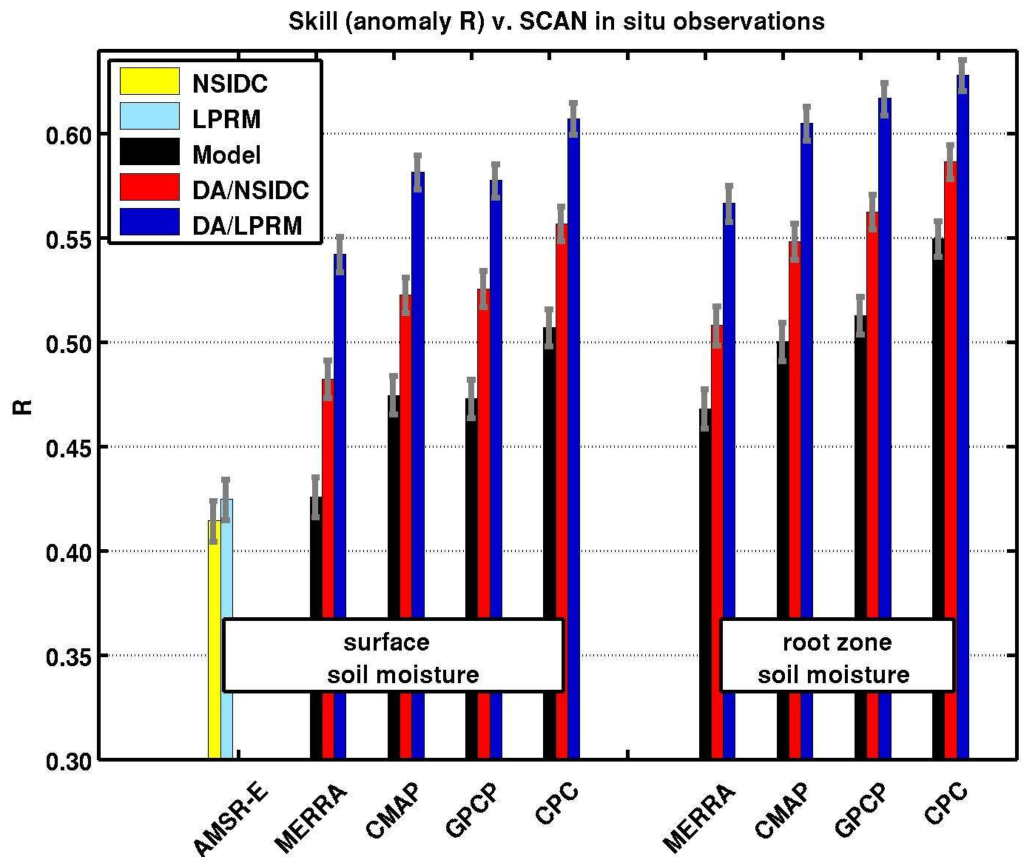
Cross-mask locations and times with qualitative satellite and in situ data



Australia (Murrumbidgee):

- point measurements
- satellite pixel average (dense point-scale obs)

AMSR-E Soil Moisture Assimilation



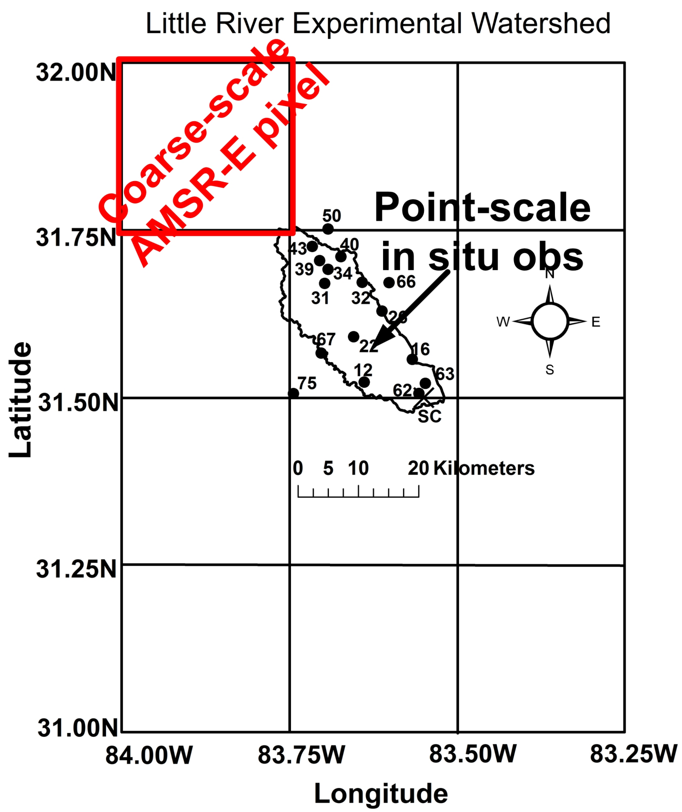
- precipitation corrections to MERRA: CMAP, GPCP, CPC
- 2 different AMSR-E soil moisture retrieval products: NSIDC, LPRM
- ensemble Kalman filter

(*Liu et al., JHM, 2011*)

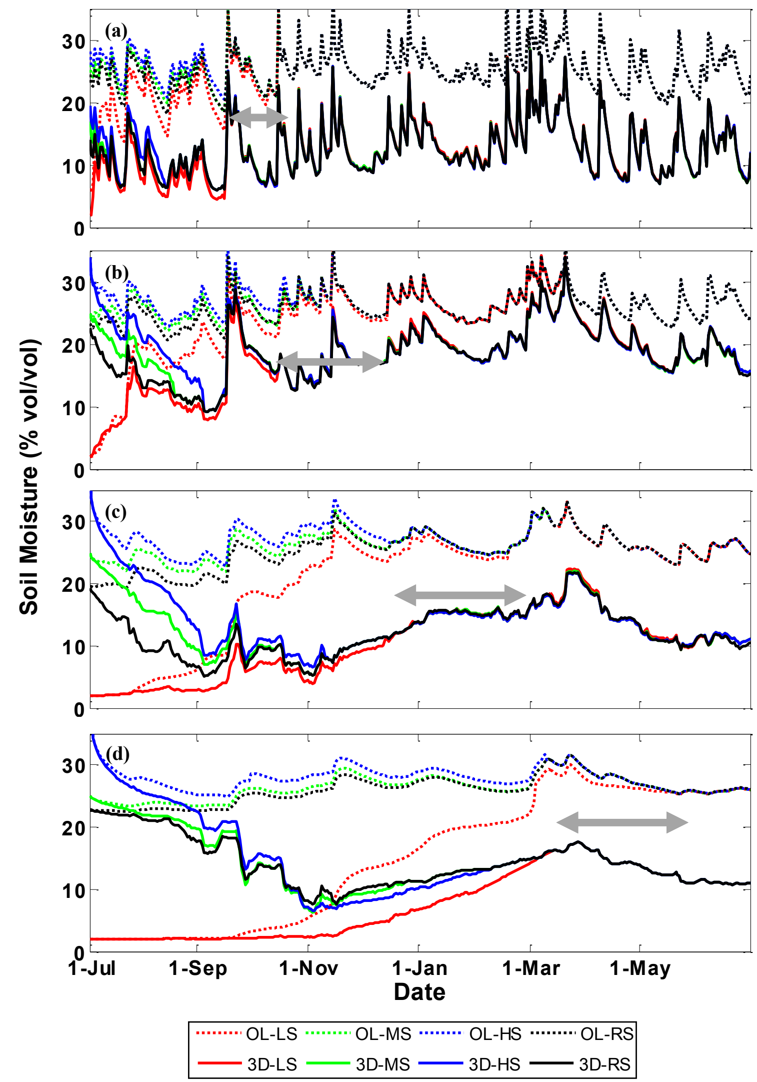
Soil moisture (anomaly) skill increases with
- precipitation corrections, and
- assimilation of surface soil moisture retrievals

Improved root-zone soil moisture

AMSR-E Soil Moisture Assimilation



↓ increasingly deeper soil layers:



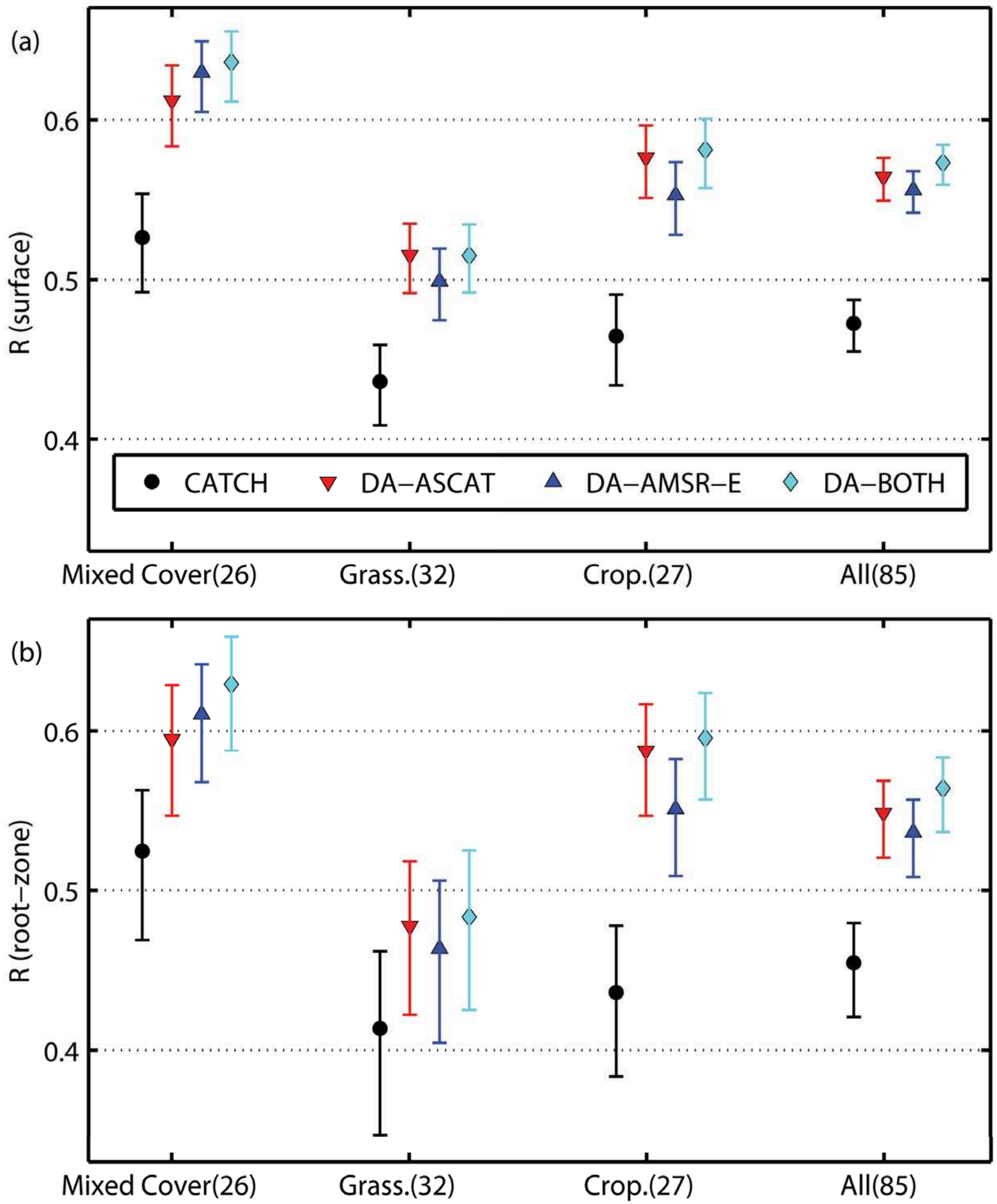
- Little River CalVal site
- coarse-scale AMSR-E downscaling (3D-filter)
- initialize with low, medium, high soil moisture

(*Sahoo et al., AWR, 2012, in review*)

Assimilation helps balancing the model and reduces spinup time

AMSR-E and ASCAT Soil Moisture Assimilation

State updating with **passive** (AMSR-E) and **active** (ASCAT) microwave obs

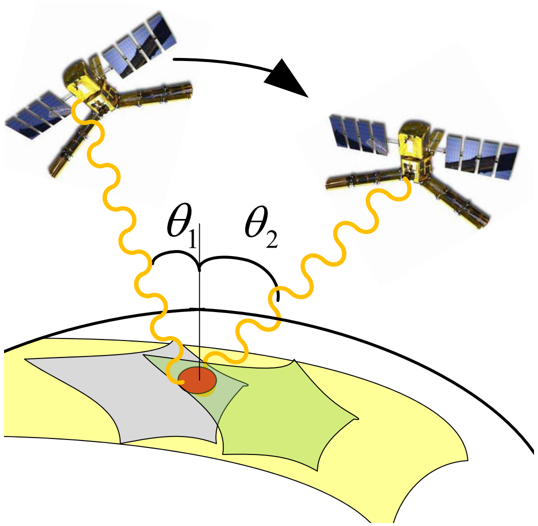


- Skill: anomaly R [-] (+ confidence intervals)
- 2007-2010
- SCAN/SNOTEL (US) + Murrumbidgee (AUS)

Significant skill increase:
- AMSR-E and ASCAT assimilation
- surface and root-zone soil moisture
- mainly low vegetation

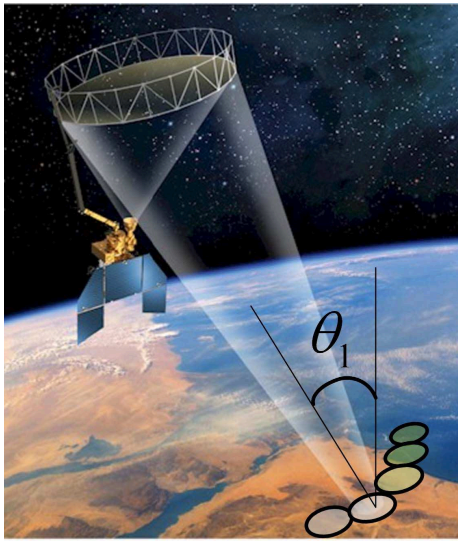
(*Draper et al., GRL, 2012, accepted*)

SMOS (ESA, Soil Moisture Ocean Salinity)



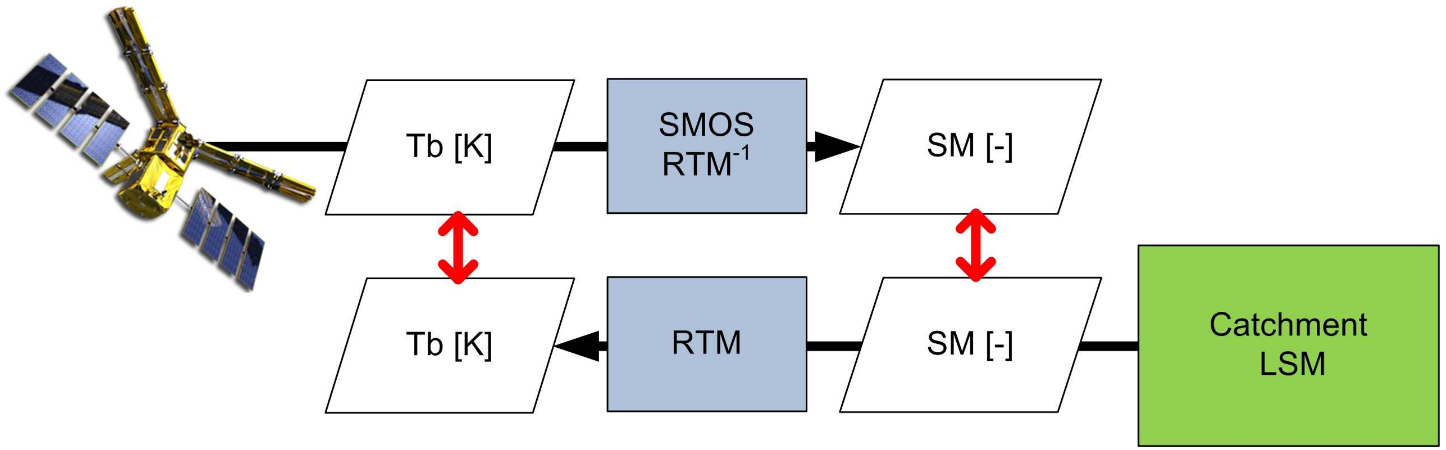
- launched November 2009
- L-band radiometer
- sensing depth = 5 cm
- 40 km resolution

SMAP (NASA, Soil Moisture Active Passive)

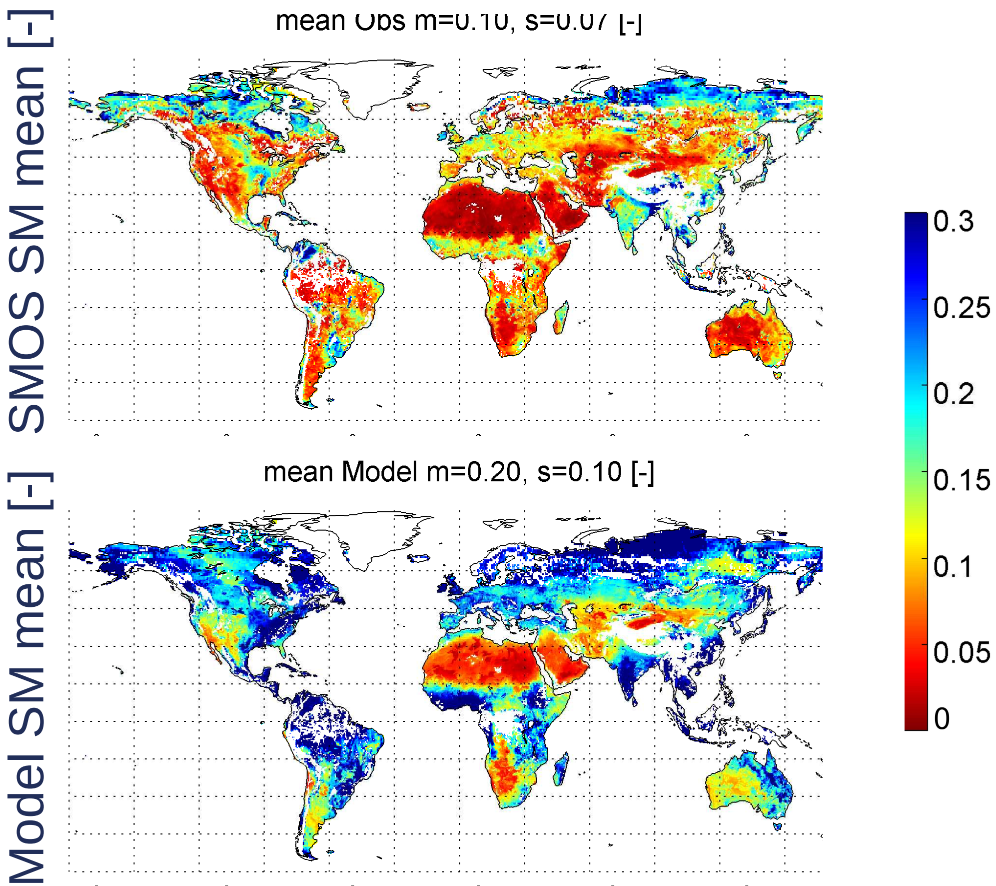


- launch 2014
- L-band radiometer/radar
- sensing depth = 5 cm
- 3-40 km resolution

→ Assimilate soil moisture retrievals and brightness temperatures (separately) from SMOS to prepare for SMAP

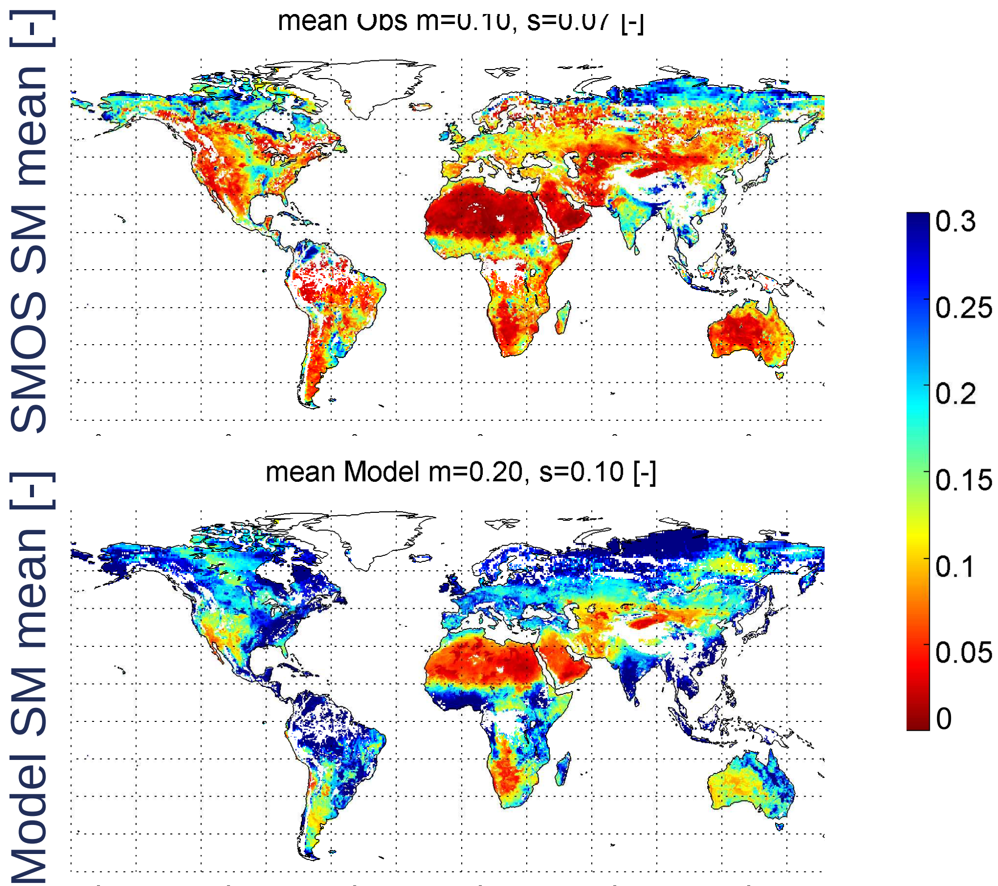


- **GEOS-5 Catchment LSM**:
  - 36 km, 1 Jan 2010 - 1 Nov 2011
  - Fortuna 2.3 version with 5 cm surface layer, MERRA forcings
- **Radiative Transfer Model (RTM)**:
  - $\tau - \omega$ model: soil moisture/temperature, vegetation water/temperature $\rightarrow$ Tb
- **Confront Model with Observations:**:
  - soil moisture: bias, LSM soil parameterization; anomaly DA
  - Tb: RTM parameter estimation; assimilation



Model SM is wetter & less variable (not shown) than **SMOS SM**

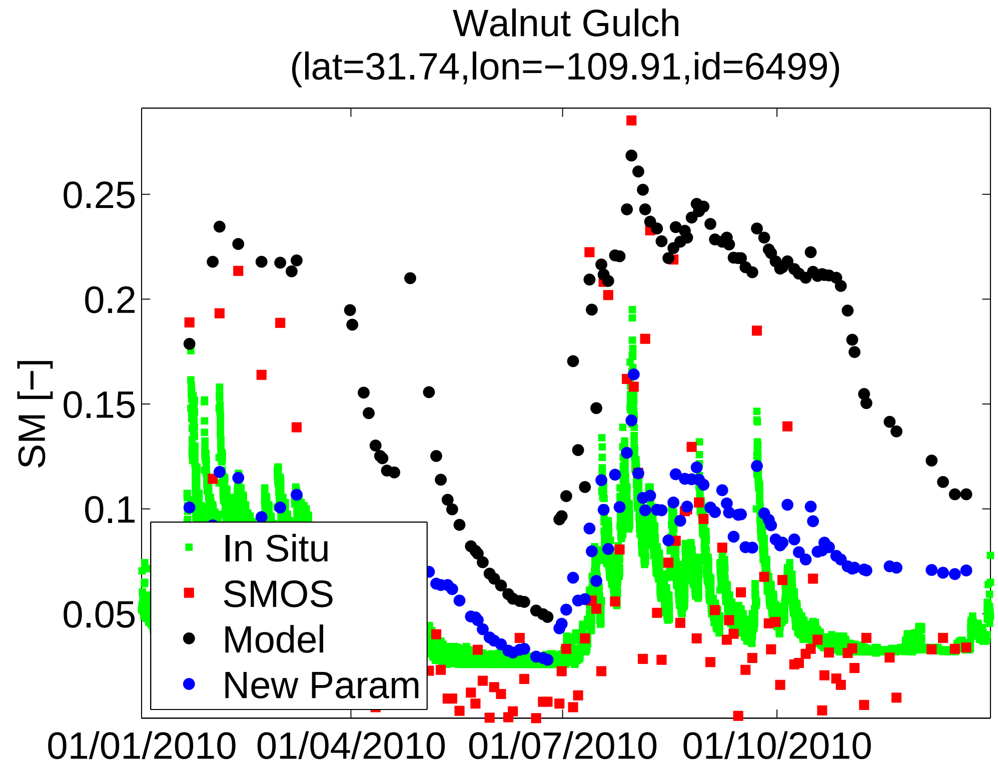
- bias → CDF-matching
- anomaly assimilation



Model SM is wetter & less variable (not shown) than **SMOS SM**

- bias $\longrightarrow$ CDF-matching
- anomaly assimilation

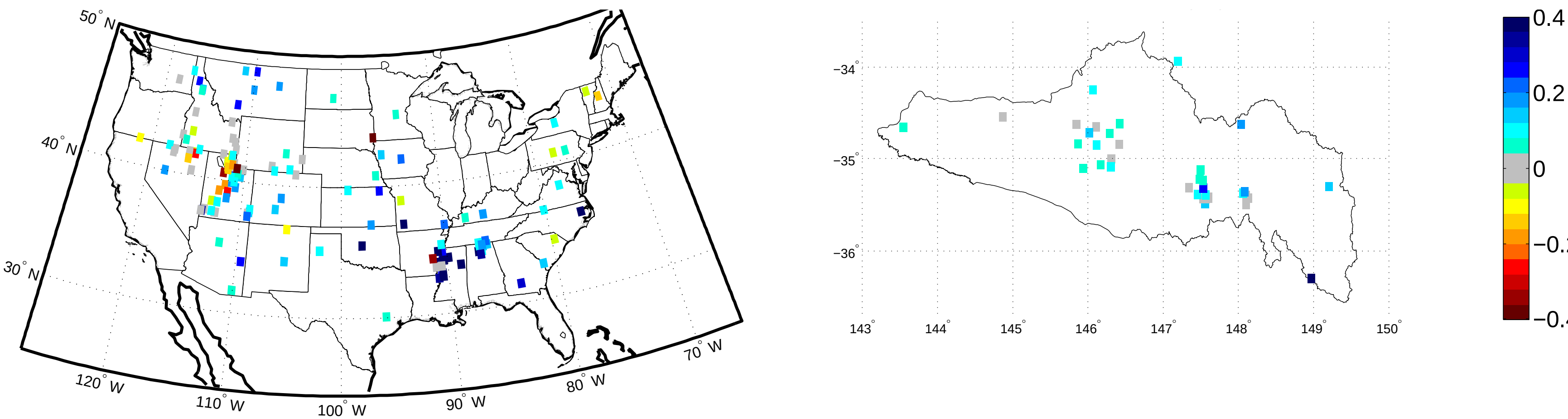
Work on partial bias reduction:



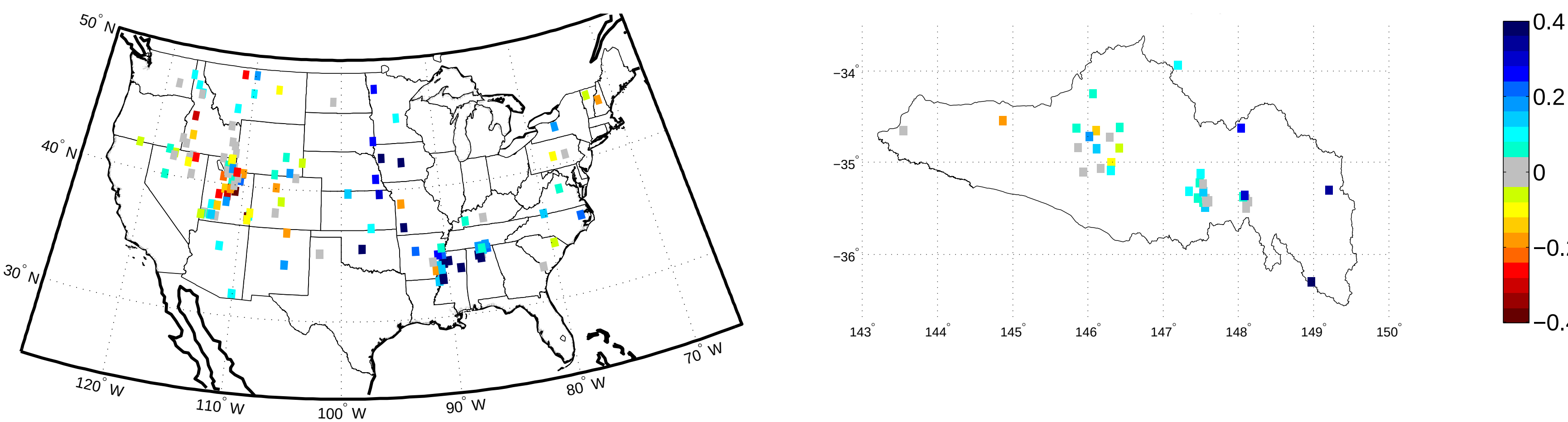
- update global soil texture, include organic material
- update soil hydraulic parameters
- account for gravel corrections

SMOS Retrieval Assimilation

Surface Soil Moisture: ΔR [-]



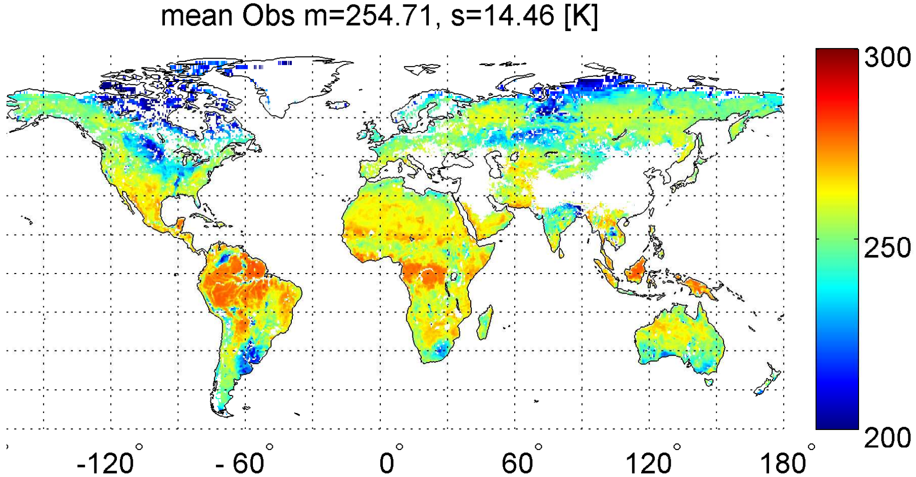
Root-Zone Soil Moisture: ΔR [-]



SMOS retrieval assimilation improves soil moisture estimates for both the surface and root-zone.

SMOS Tb Calibration

Limit model bias before data assimilation



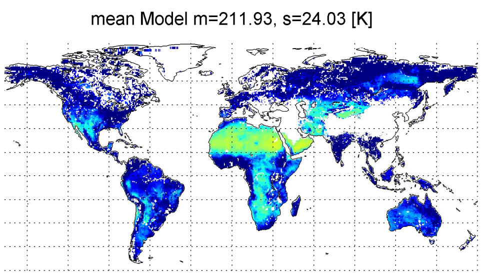
1 Jan 2011 - 1 Nov 2011

$\Leftarrow$ **SMOS observed** Tb, H-pol, 42.5^{o}

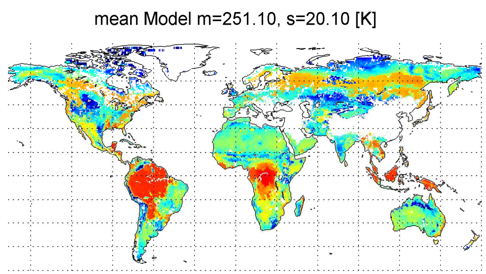
$\Downarrow$ **Model predictions** Tb, H-pol, 42.5^{o}

- with prescribed RTM parameters (SMAP, LSMEM literature, ECMWF)
- after RTM parameter estimation (1 Jan 2010 - 1 Jan 2011)

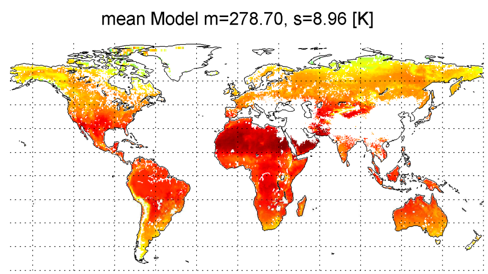
SMAP



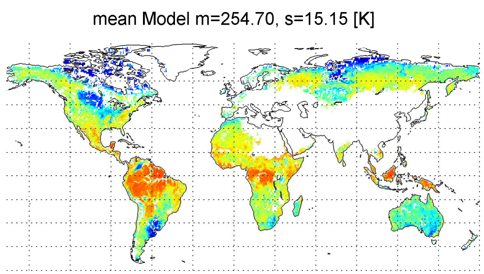
LSMEM



CMEM-EC



Calibrated



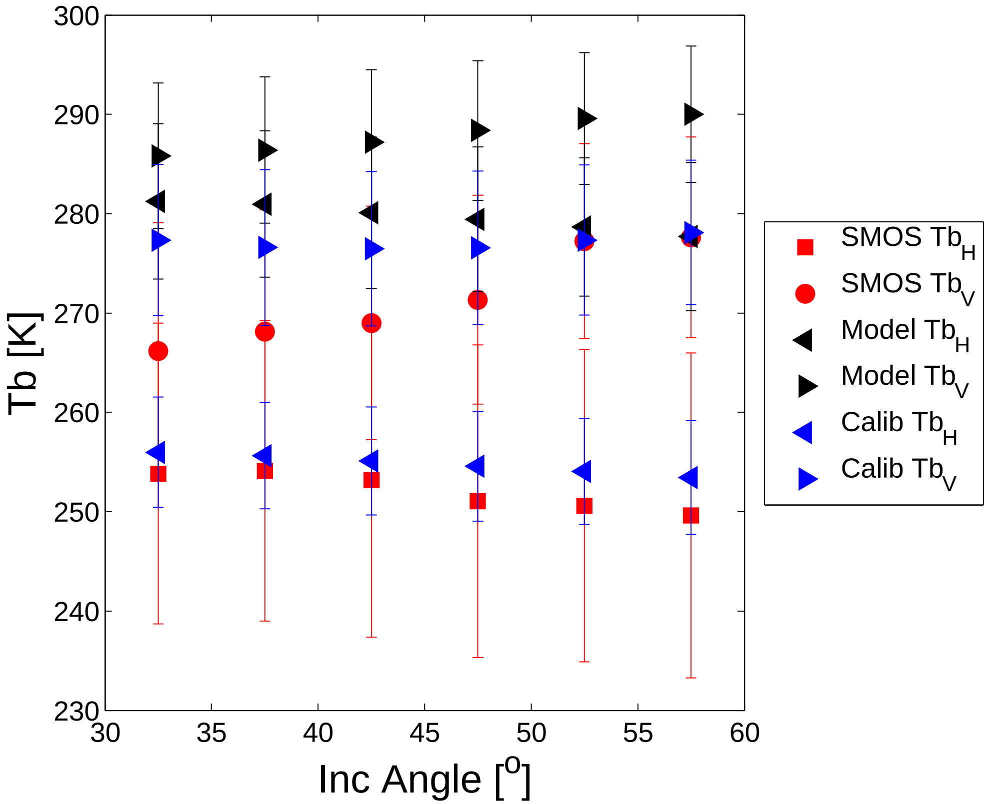
- Split sample: Unbiased Tb predictions after multi-angular Tb calibration

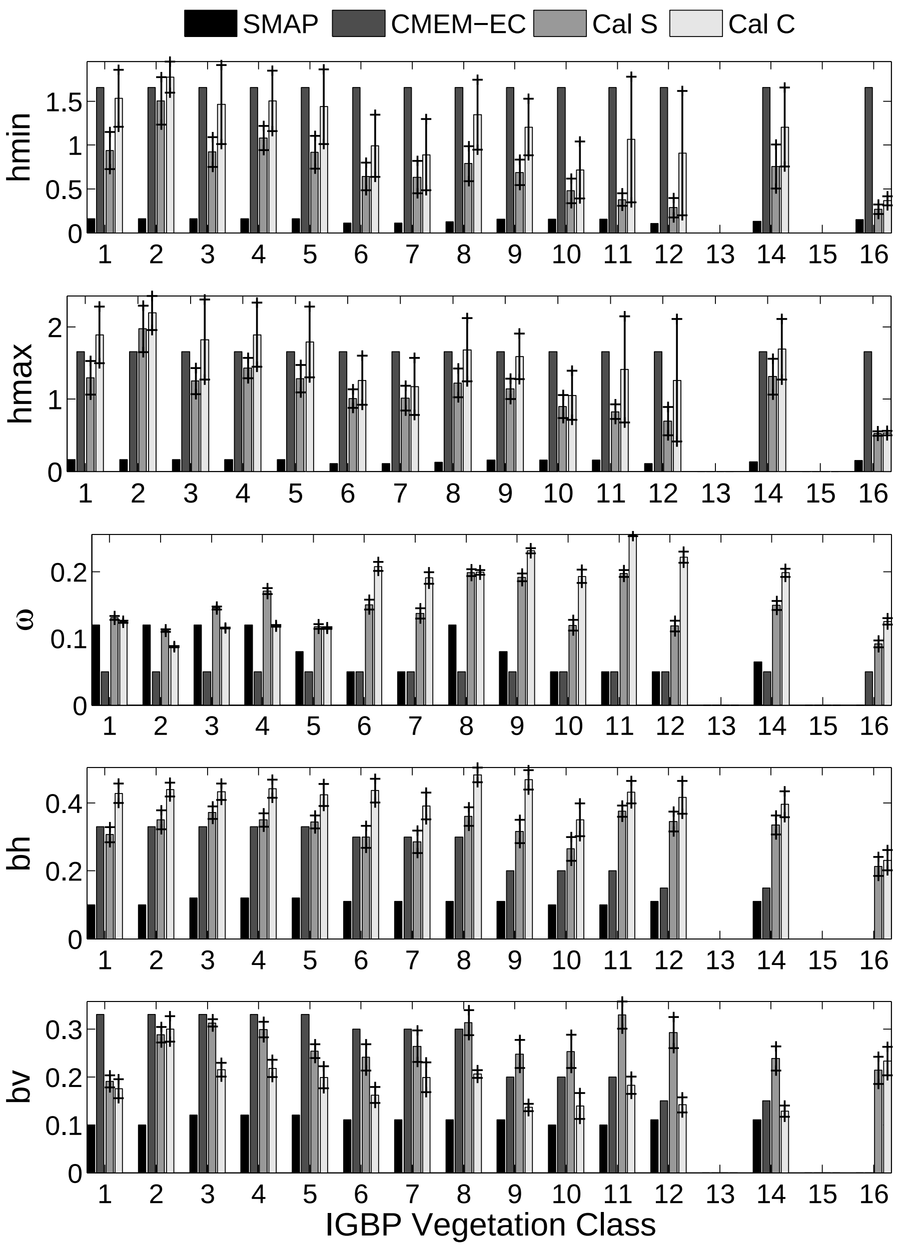
SMOS Tb Calibration

Method: At each individual pixel, minimize difference in:

- climatological mean (6 angles)
- temporal variability (6 angles)
- calibrated parameter and best guess

Little River CalVal Watershed

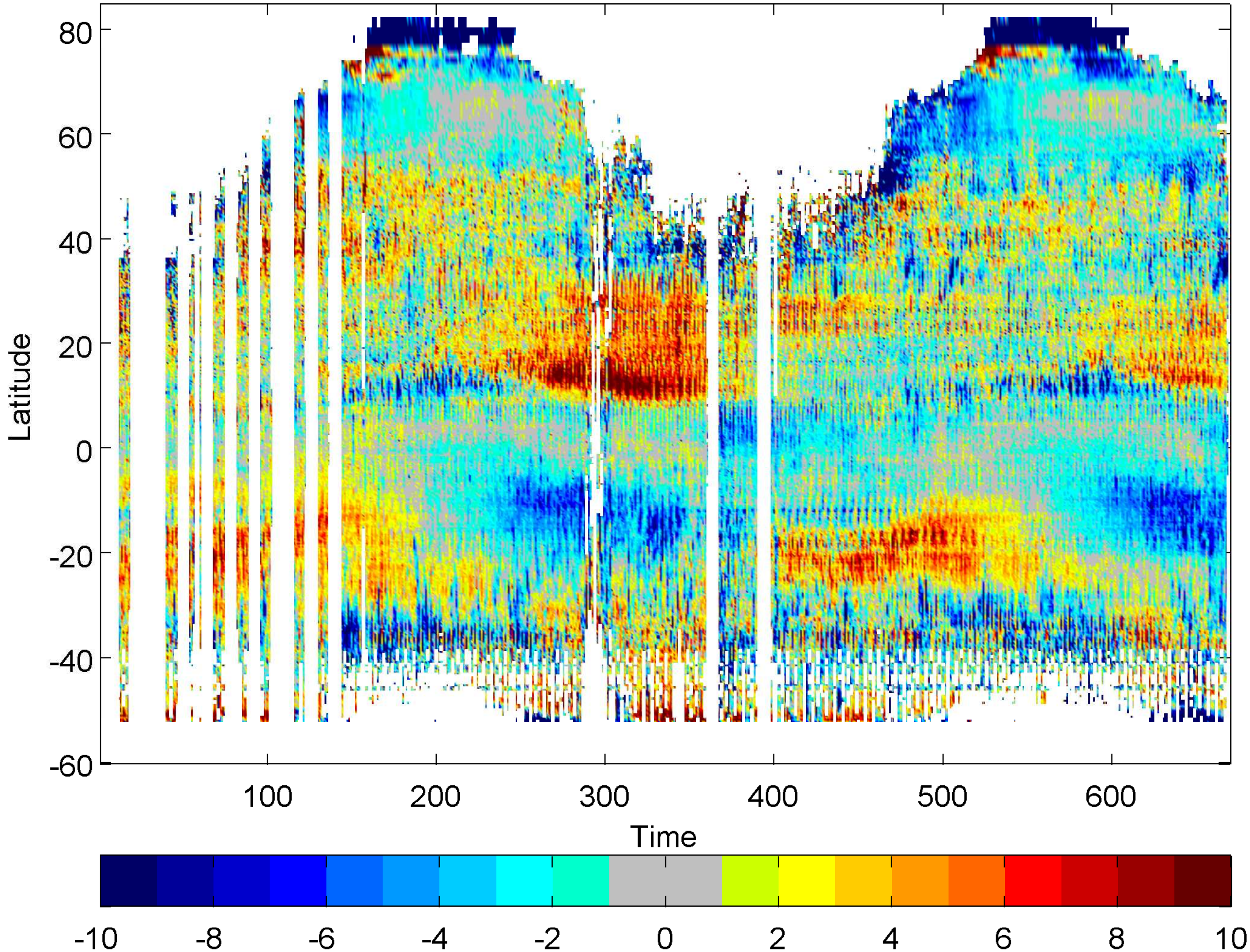




SMOS Tb Validation

1 January 2010 - 1 November 2011:

multi-angle average of H-pol Tb observation-minus-forecasts [K]



Some limited seasonal bias remaining after climatology calibration

SMOS Retrieval *vs.* Radiance Assimilation

SCAN/SNOTEL	Surface			Root-zone	
SM DA	SMOS	OL	DA	OL	DA
R^* [-]	0.52	0.59	0.67	0.64	0.68
	(0.37,0.65)	(0.45,0.69)	(0.54,0.76)	(0.53,0.73)	(0.58,0.76)
ubRMSE** [m^3/m^3]	0.072	0.060	0.056	0.049	0.046
Tb DA	SMOS	OL	DA	OL	DA
R^* [-]	0.52	0.58	0.70	0.66	0.65
	(0.37,0.65)	(0.43,0.70)	(0.57,0.79)	(0.55,0.75)	(0.52,0.75)
ubRMSE** [m^3/m^3]	0.072	0.061	0.055	0.046	0.045

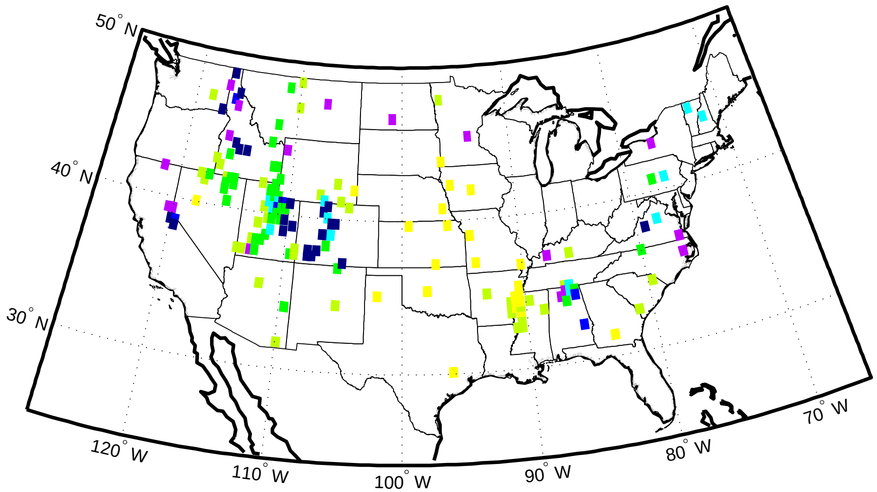
* with 95% confidence intervals; ** target uncertainty for SMAP = 0.04 m^3/m^3

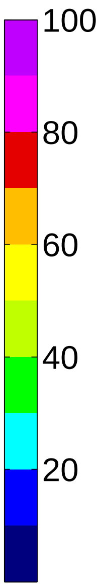
- $\surd$ increase in R, decrease in RSME
- not screened for complex topography; see next slide
- Tb DA still includes seasonal bias, non-optimal RTM (preliminary results!)
- number of analysis steps different for retrieval and radiance assimilation; see next slide

Assimilation Time Steps

% assimilation time steps with

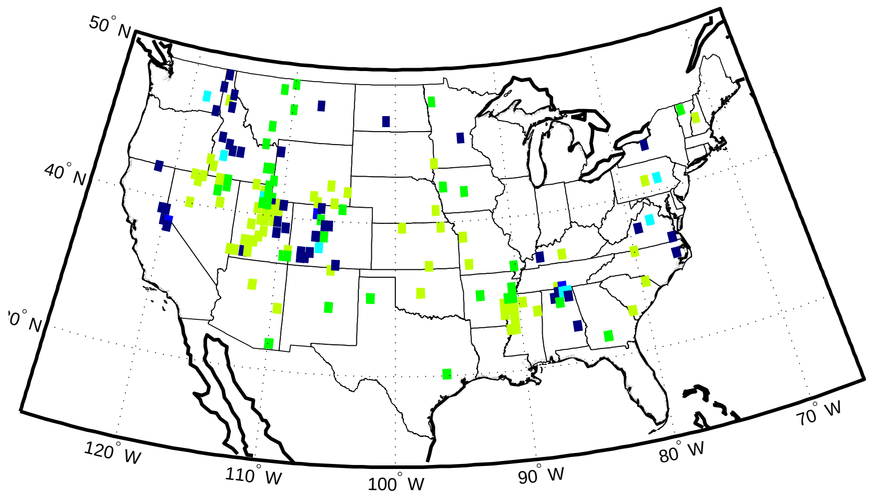
SM only



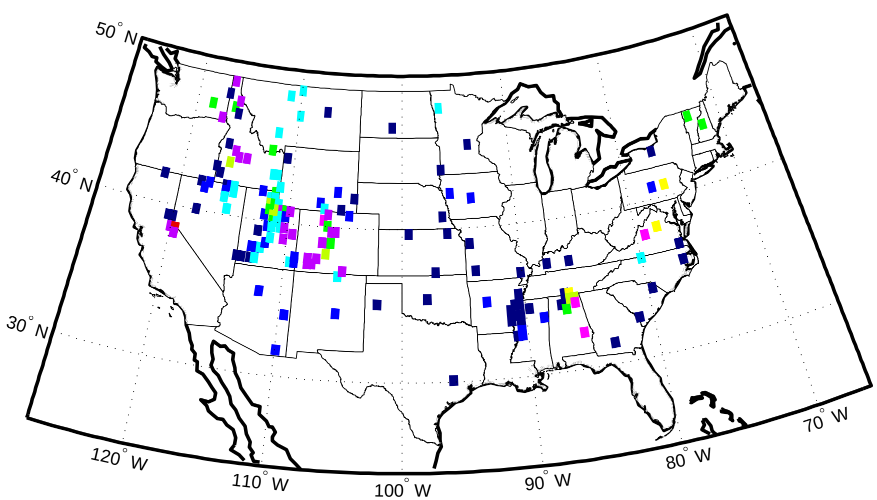


% assimilation time steps with

both SM and Tb

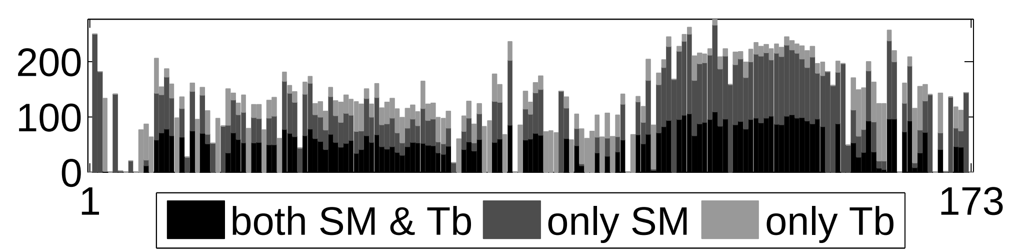


Tb only



Only half of the time steps have both valid SM retrievals and Tb observations available. Main reason: Tb is limited to alias-free zones only, while SM is not.

number of assimilation time steps

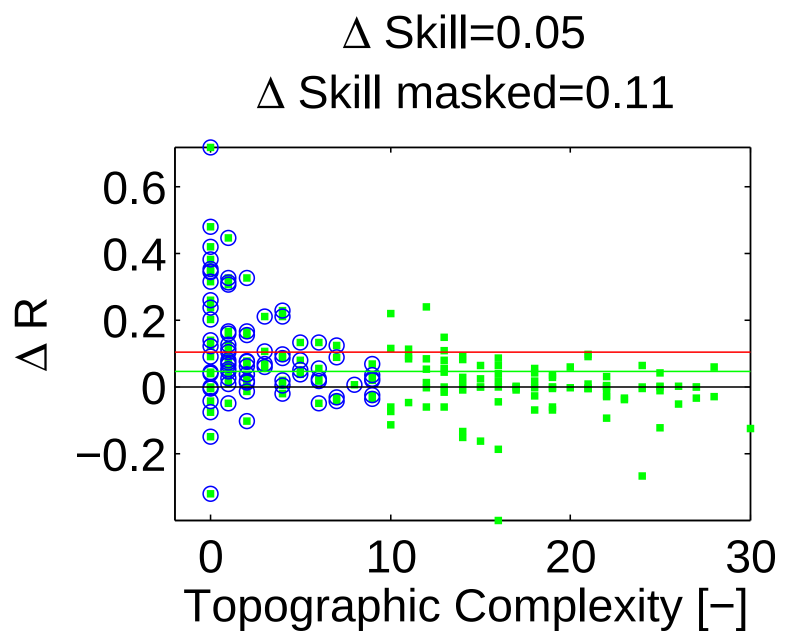


Most data in Great Plains

SMOS Retrieval *vs.* Radiance Assimilation

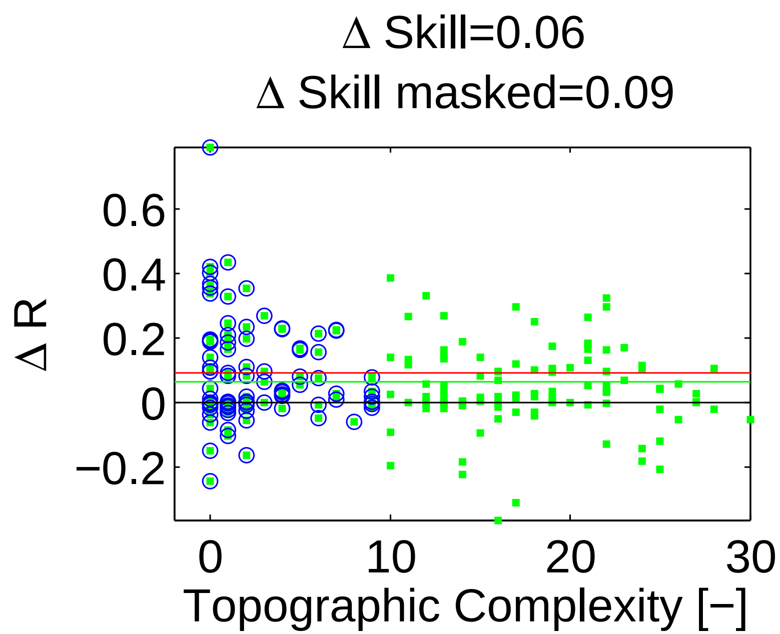
Surface soil moisture skill, incl. identical amount of time steps (analysis and forecast, during 1 Jan 2010 - 1 Jan 2011)

Retrieval DA skill R [-]



SM retrievals may not be optimal in complex terrain

Radiance DA skill R [-]

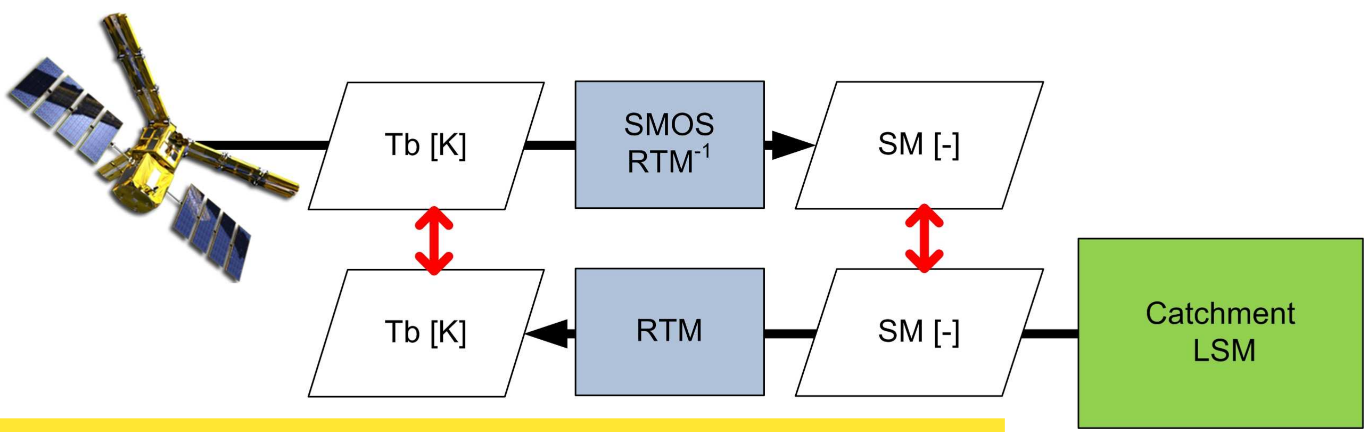


Complex terrain does not significantly affect Tb DA; work in progress

Retrieval and radiance assimilation may be more or less beneficial in particular conditions; work in progress

Soil Moisture Assimilation

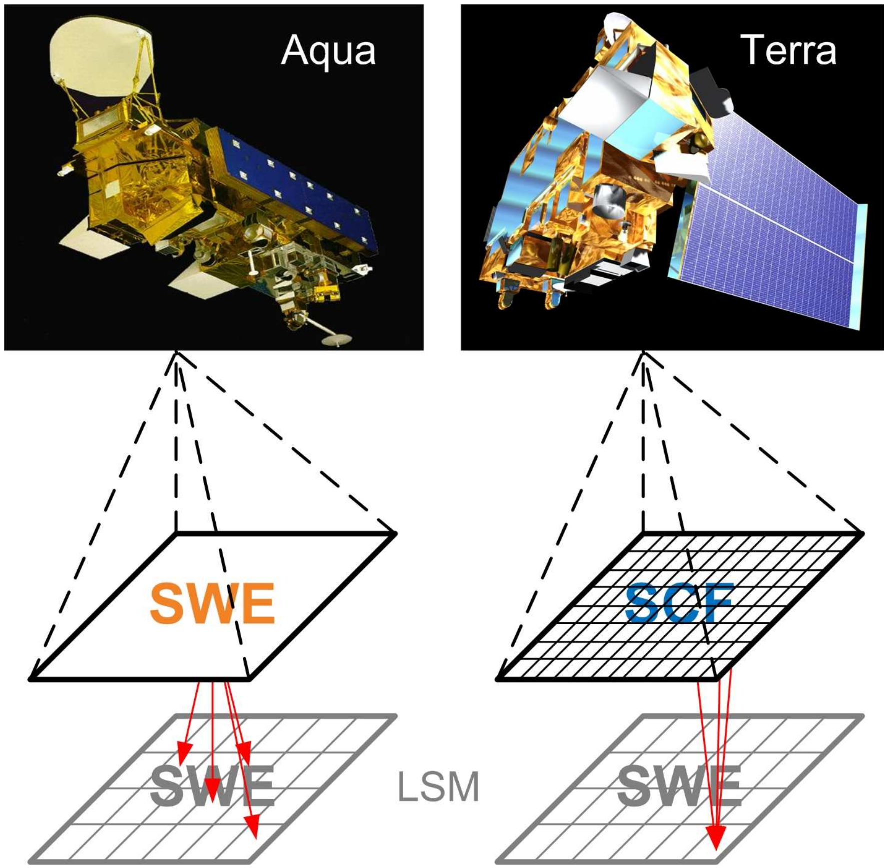
- new missions $\rightarrow$ deeper soil penetration
- retrieval assimilation (AMSR-E, ASCAT, SMOS SM into CLSM): well documented improvements in surface and root-zone soil moisture
- radiance assimilation (SMOS Tb into CLSM+RTM): promising improvements in surface and root-zone soil moisture
- climatological observation-forecast bias:
  - ☐ CLSM soil parameters optimization
  - ☐ RTM parameter calibration
- scale discrepancies: downscaling, anomaly assimilation



Preparation for SMAP L4_SM product

Snow Data Assimilation

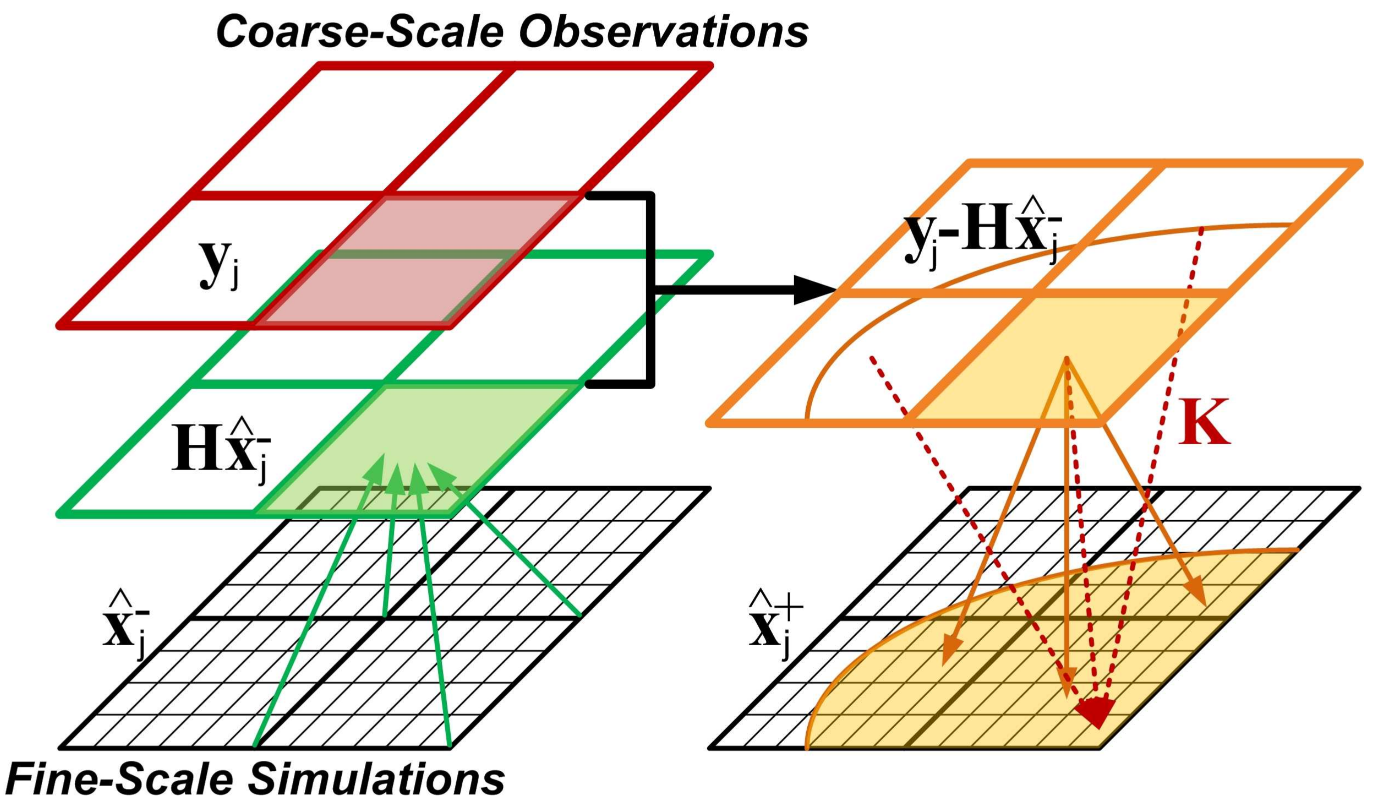
Remote Sensing of Snow



- **AMSR-E**: passive microwave sensor (radiometer), snow: dominantly 18.7/36.5 GHz, 25 km resolution
- **MODIS**: visible/near infrared, spatial resolution: 500 m

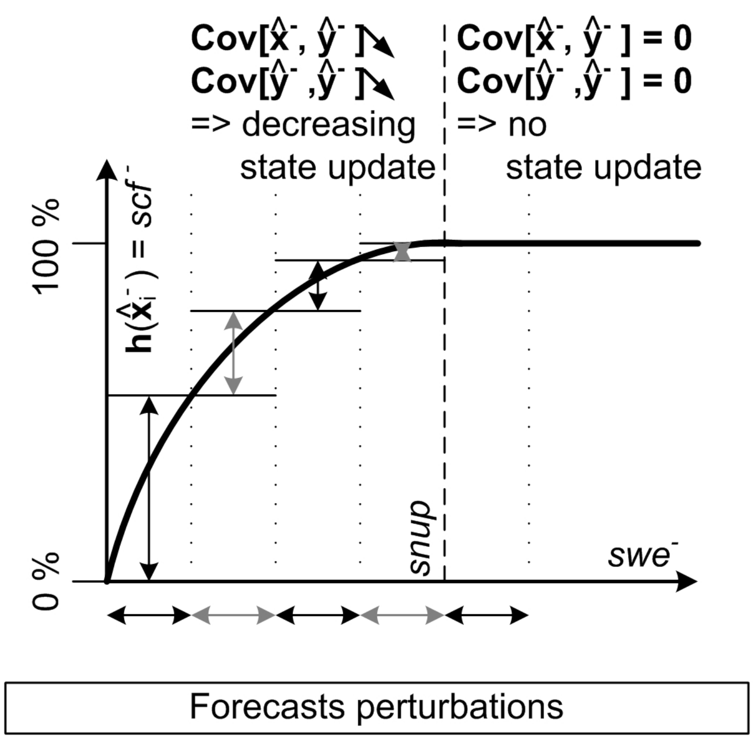
AMSR-E
- Actual measurements = brightness temperature
- Snow Water Equivalent = retrieval

- 25 km AMSR-E snow water equivalent (SWE) $\longrightarrow$ downscaling
- 500 m MODIS snow cover fraction (SCF) $\longrightarrow$ update SWE



- snow water equivalent = coarse-scale estimate of water in the snowpack
- 3D filter, using multiple coarse obs for each fine-scale update
- spatially correlated forecast perturbations
- no boundary effects, horizontal propagation

- snow cover fraction = fine-scale indirect/incomplete measurement of snowpack
- observation operator converts SWE to SCF
- model divergence $\rightarrow$ rule-based update

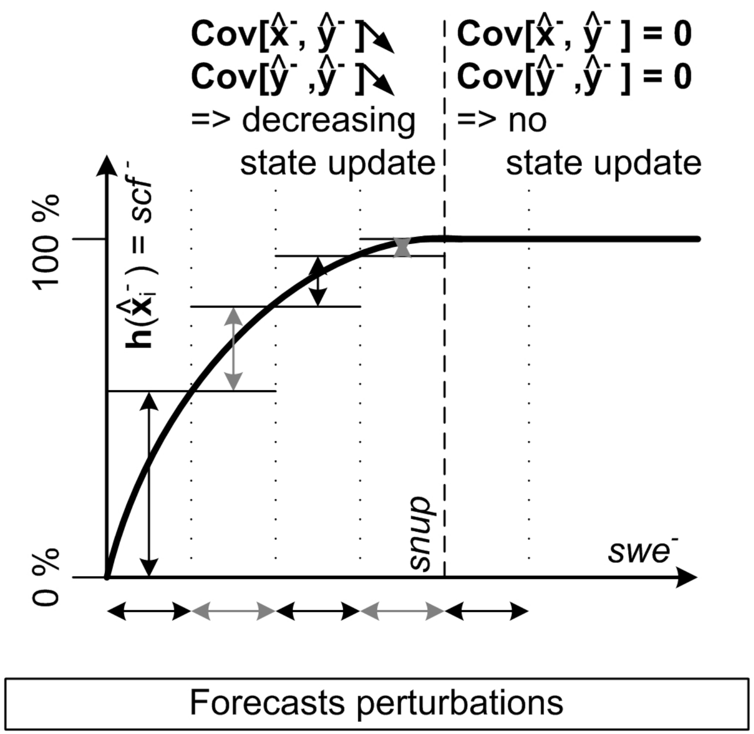


$$\hat{\mathbf{x}}_i^- = \begin{pmatrix} swe^- \\ snd^- \end{pmatrix}_i$$

$$scf^- = \hat{\mathbf{y}}_i^{j-} \equiv \mathbf{h}_i(\hat{\mathbf{x}}_i^{j-})$$

SCF Assimilation

- snow cover fraction = fine-scale indirect/incomplete measurement of snowpack
- observation operator converts SWE to SCF
- model divergence $\rightarrow$ rule-based update



$$\hat{\mathbf{x}}_i^- = \begin{pmatrix} swe^- \\ snd^- \end{pmatrix}_i$$

$$scf^- = \hat{\mathbf{y}}_i^{j-} \equiv \mathbf{h}_i(\hat{\mathbf{x}}_i^{j-})$$

If no predicted snow:

if $[scf^{obs} - scf^-] > 0.5$,

then add snow

SCF Assimilation

- snow cover fraction = fine-scale indirect/incomplete measurement of snowpack
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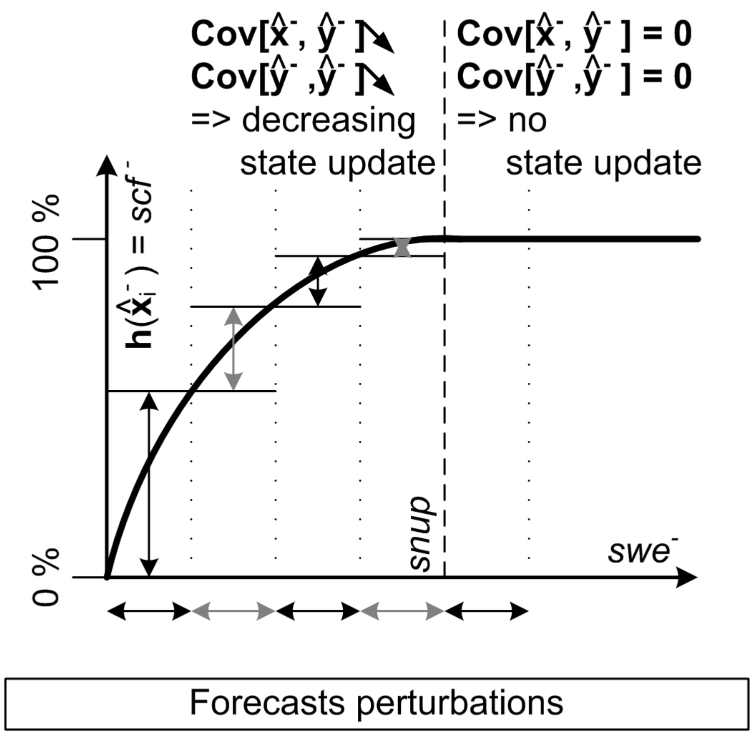


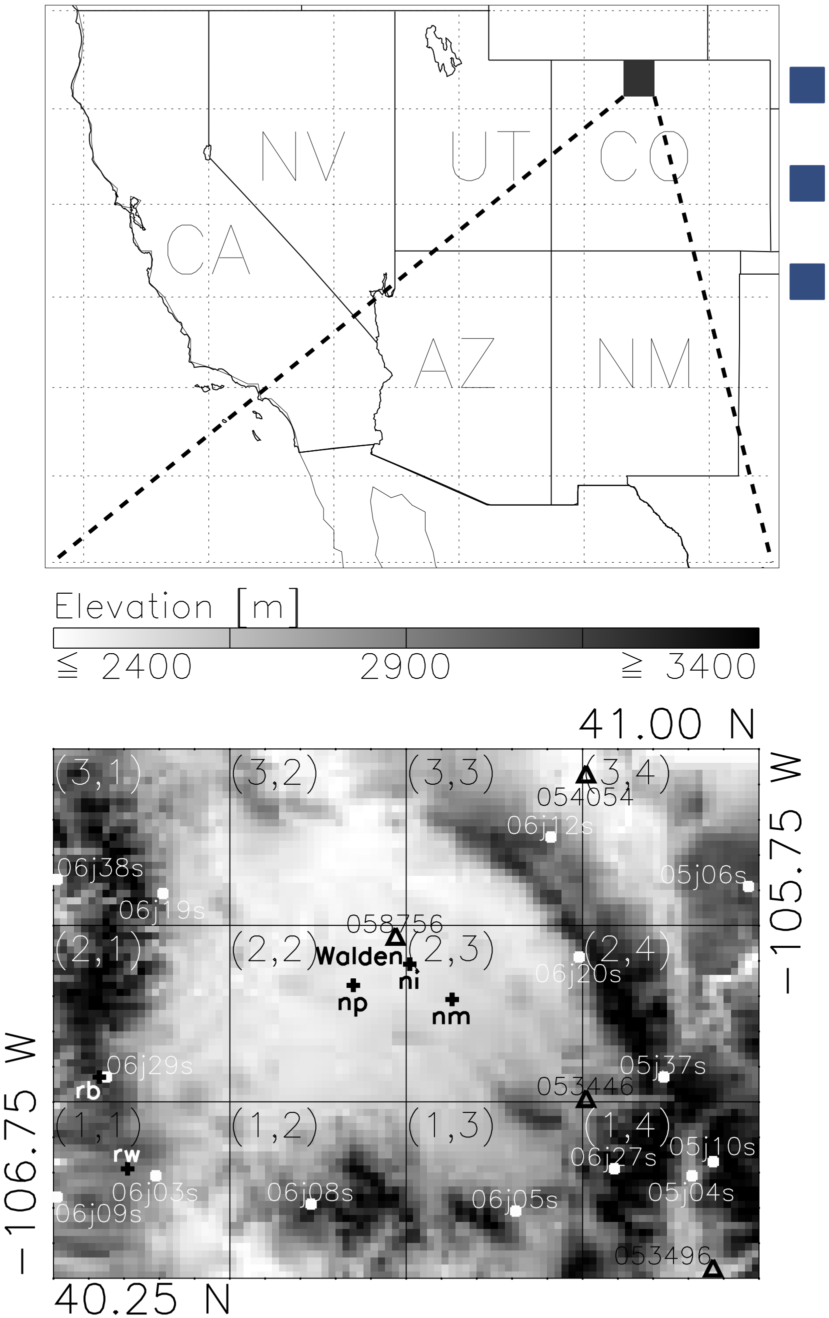
$$\hat{\mathbf{x}}_i^- = \begin{pmatrix} swe^- \\ snd^- \end{pmatrix}_i$$

$$scf^- = \hat{\mathbf{y}}_i^{j-} \equiv \mathbf{h}_i(\hat{\mathbf{x}}_i^{j-})$$

If no predicted snow:
if $[scf^{obs} - scf^-] > 0.5$,
then add snow

If full cover snow (no spread):
if $[scf^{obs} - scf^-] < 0.5$,
then remove snow

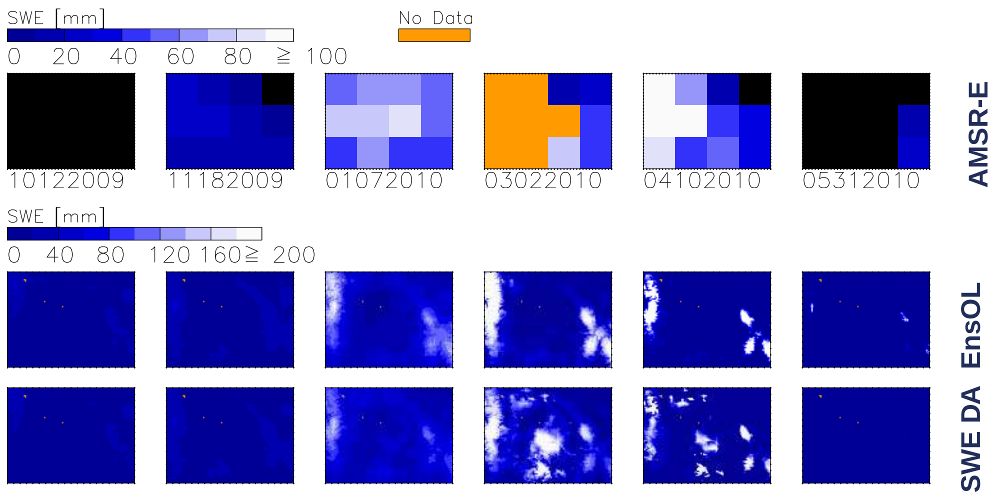
Study Area



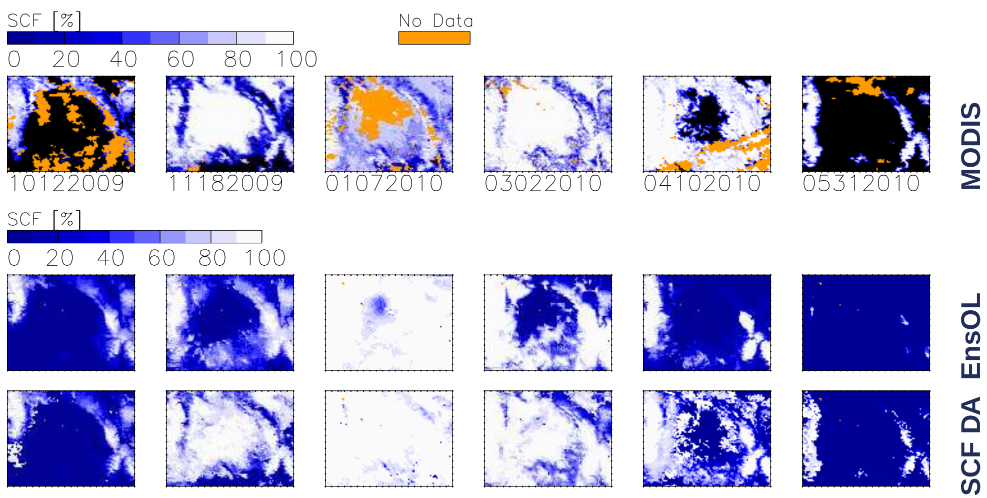
- North Park, CO, 75×100 km^2
- period 2002-2010
- validation: SNOTEL (○), COOP (△)

AMSR-E & MODIS DA: Multi-Sensor, Multi-Scale

25 km **AMSR-E** snow water equivalent (SWE) downscaling:



500 m **MODIS** snow cover fraction (SCF) → update SWE:

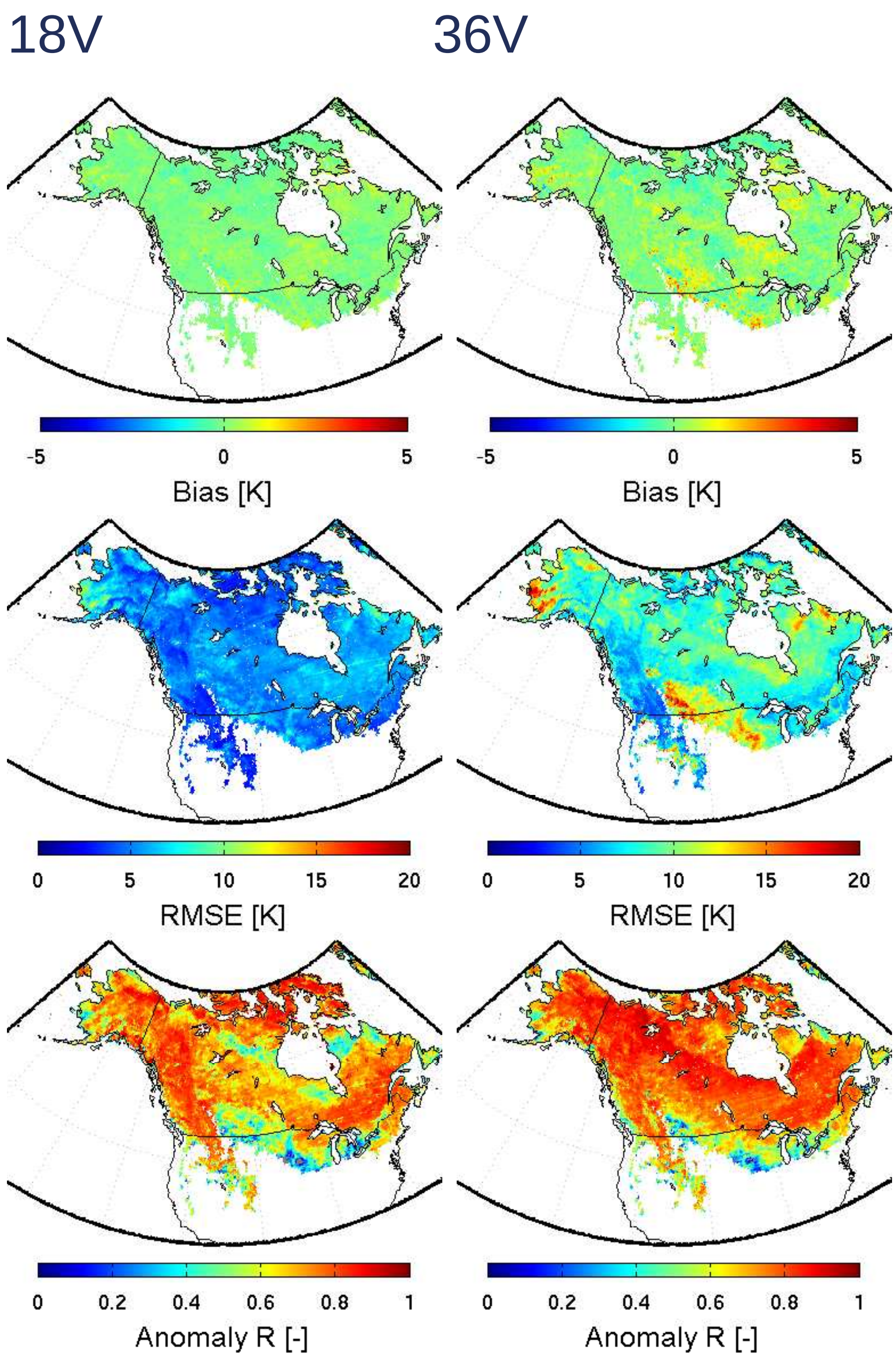


Joint (multi-scale) SWE and SCF assimilation: improved results in shallow snow locations (only)

- AMSR-E SWE: lacks realistic interannual variability, mainly in deep snow
- MODIS SCF DA: improved timing of snow accumulation onset

(*De Lannoy et al., WRR, 2012*)

AMSR-E Brightness Temperature



Prepare for the direct radiance assimilation of AMSR-E observations

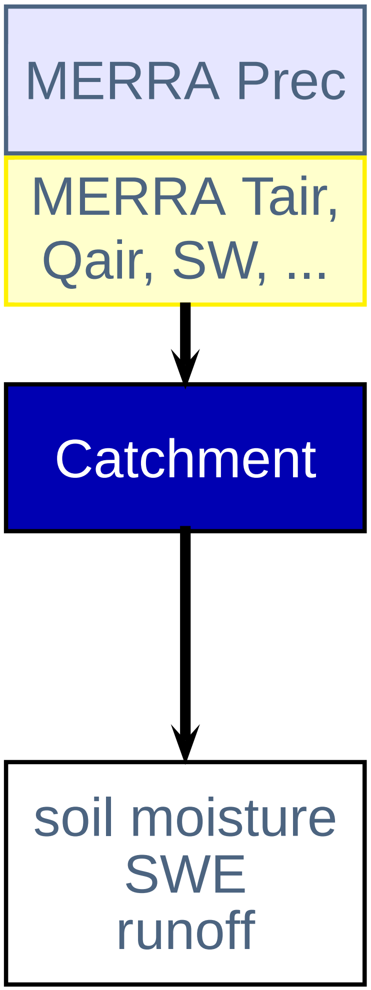
- artificial neural network
- input: snow density, water equivalent, liquid water content snow/air/soil temperatures
- output: Tb_{H10}, Tb_{V10}, Tb_{H18}, Tb_{V18}, Tb_{H36}, Tb_{V36}
- training & validation: split sample

ANN provides robust predictions of multi-channel/pol Tb (difficulty: ice layers)

(Forman et al., IEEE/TGARS, 2012, submitted)

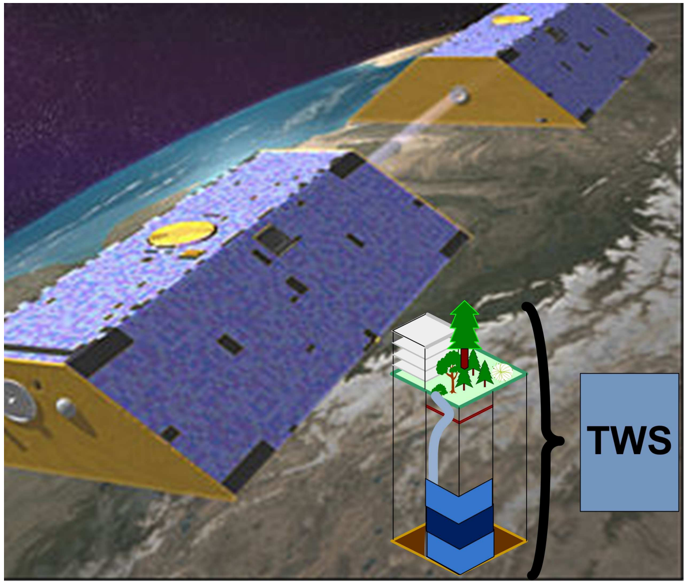
Terrestrial Water Storage Assimilation

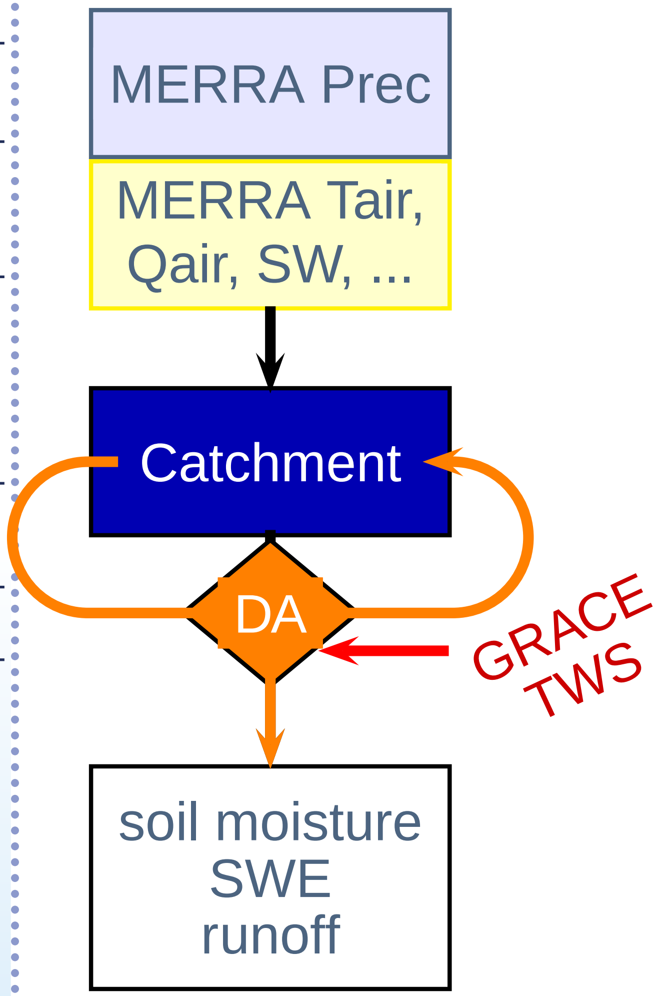
GRACE TWS



Total Water Storage = soil moisture + groundwater + vegetation + snow (SWE)

- monthly, ∼200 km resolution mass anomalies (with respect to a multi-year mean gravity field)
- partitioning into storage components
- ensemble Kalman smoother





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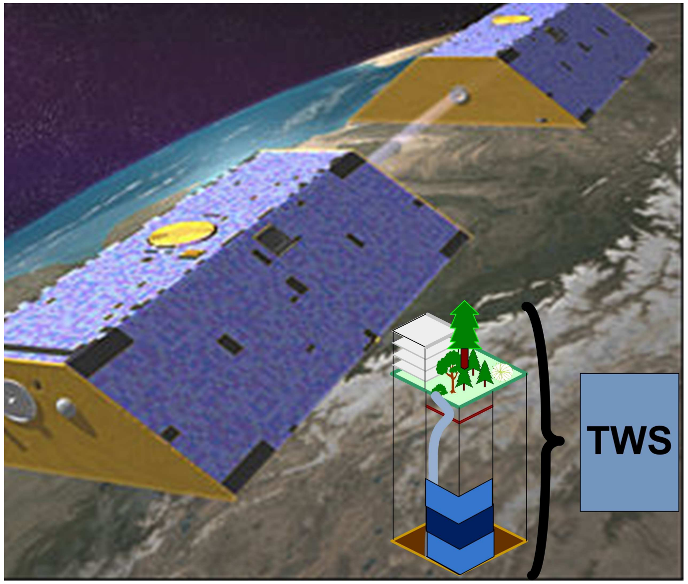
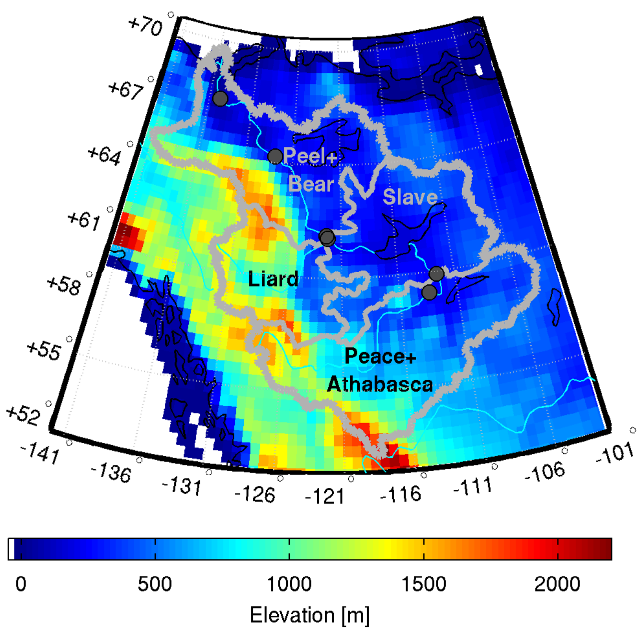
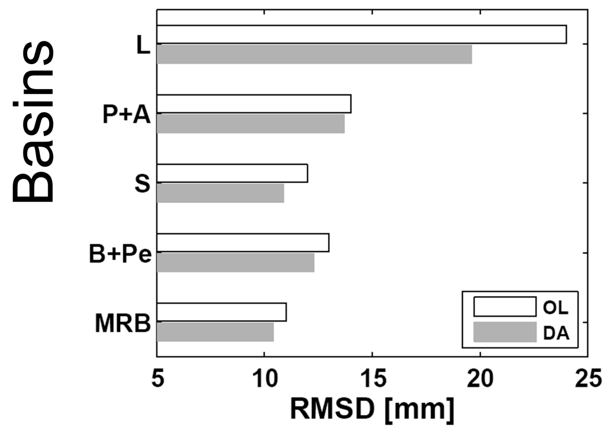


- validation against runoff and SWE in the Mackenzie river basin (2002-2008)
- GRGS product assimilated without post-glacial rebound correction

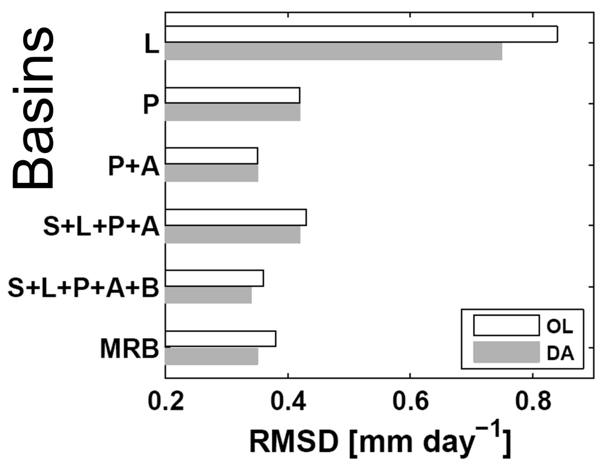


⇒ assimilation (■) of TWS improves individual storage components (SWE and runoff) over the open loop (□)

SWE Validation vs CMC



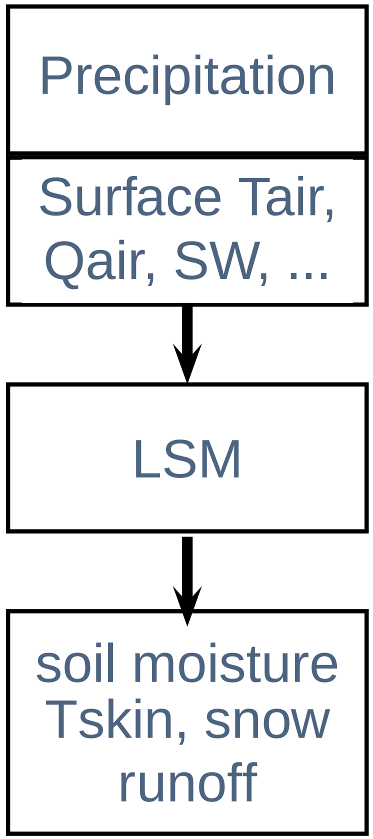
Runoff Validation vs Gages



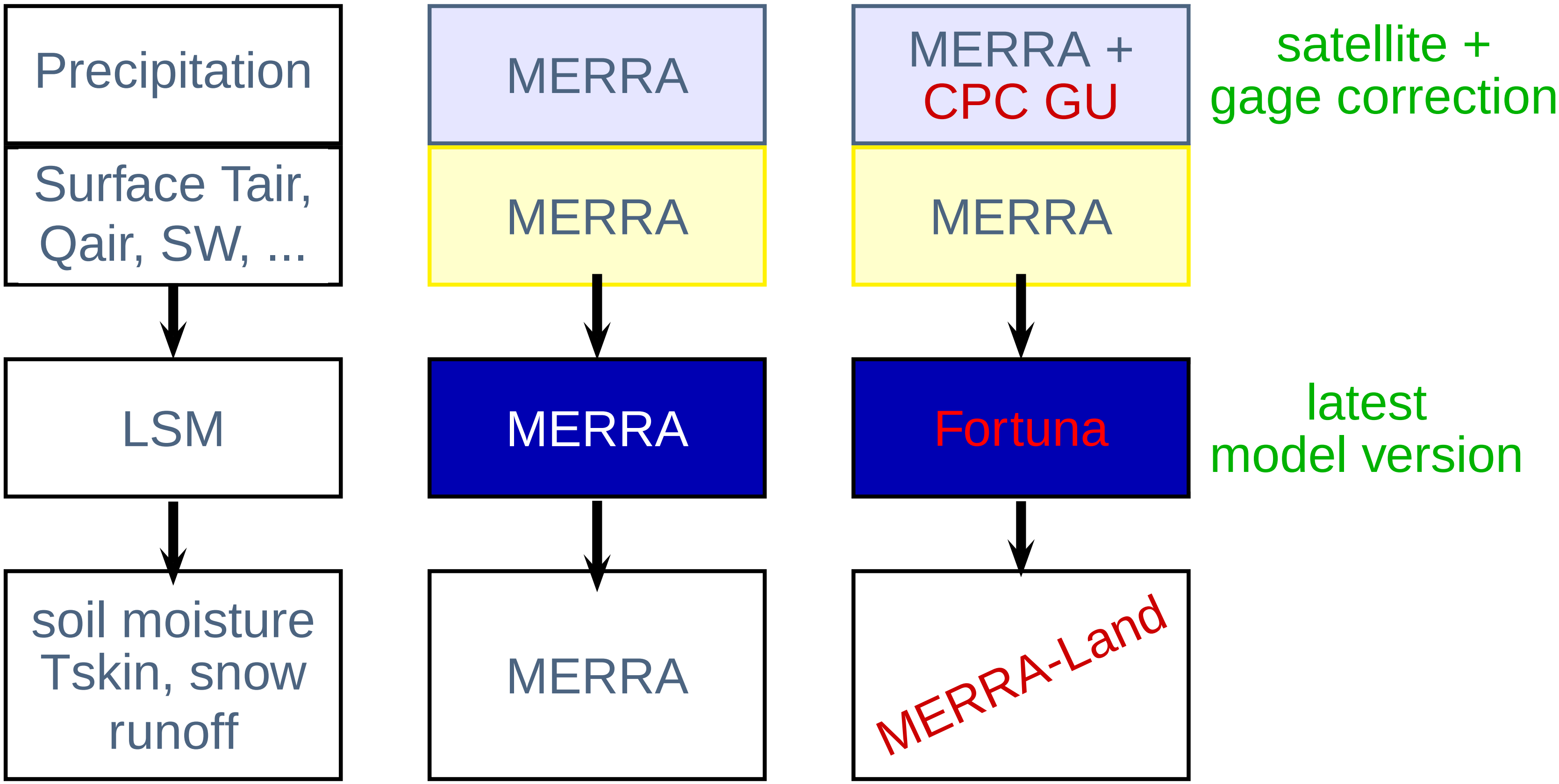
(Forman et al., WRR, 2012)

Modeling, Re-Analysis

MERRA and MERRA-Land



MERRA and MERRA-Land



- MERRA: 1979-present (updated w/ $\sim$1 month latency), global, Lat=0.5^{o}, Lon=0.67^{o}, 72 vertical levels
- MERRA-Land: Enhanced product for land surface hydrological applications (*Reichle et al., J. Clim., 2011*)

$\Rightarrow$ improved soil moisture, runoff, canopy interception and latent heat flux through precipitation corrections and an enhanced model parameterization

Remaining Gaps

Observations

- sensitivity to variable of interest (e.g. snow water equivalent, soil moisture penetration depth)
- time/space gaps, resolution

Models

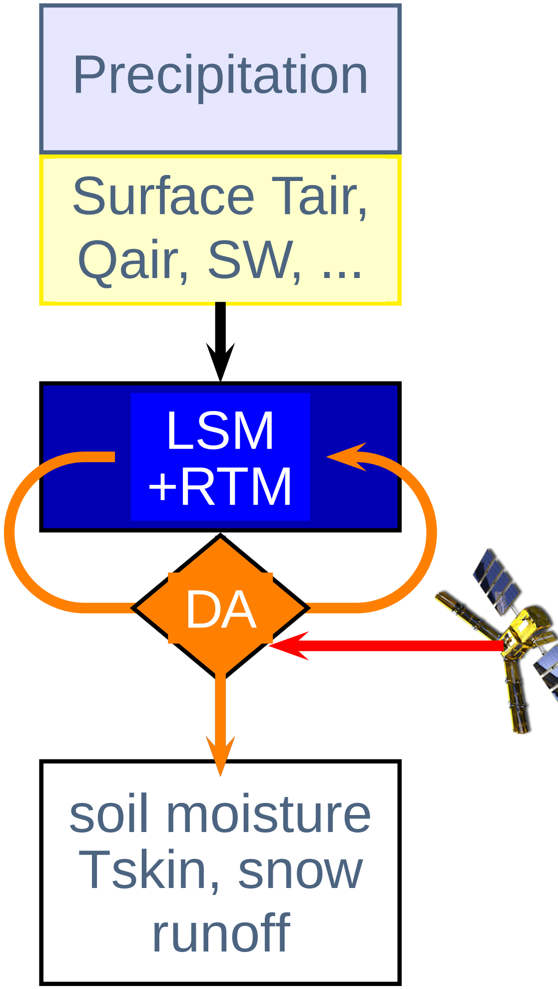
- simplified processes
- structure
- parameters

Data Assimilation

- random/systematic error specification (e.g. optimal error magnitudes, Gaussian errors?, . . .)
- coupling of land surface updates with atmosphere/ocean

Use satellite data to improve land surface estimates

- **Retrieval** data assimilation
  - ☐ AMSR-E/ASCAT/SMOS SM: improved surface and root-zone SM
  - ☐ AMSR-E SWE: interannual variability?
  - ☐ MODIS SCF: improved snow onset
  - ☐ GRACE TWS: improved SWE, runoff
- **Radiance** data assimilation
  - ☐ RTM calibration for SMOS/SMAP
  - ☐ prepare observation operator for AMSR-E snow assimilation
- **Modeling, Re-analysis**: MERRA/MERRA-Land



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